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IMPACT AND PROMISE OF NASA AEROPROPULSION TECHNOLOGY

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SUMMARY

The aeropropulsion industry in the United States has established an enviable record of leading the world in aeropropulsion for commercial and military aircraft. NASA's aeropropulsion propulsion program (primarily conducted through the Lewis Research Center) has significantly contributed to that success through research and technology advances and technology demonstrations. Some past NASA contributions to engines in current aircraft are reviewed, and technologies emerging from current research programs for the aircraft of the 1990's are described. Finally, current program thrusts toward improving propulsion systems in the 2000's for subsonic commercial aircraft and higher speed aircraft such as the High-Speed Civil Transport and the National Aerospace Plane (NASP) are discussed.

INTRODUCTION

In 1987 the aeronautics community commemorated the 50th anniversary of the first successful operation of a turbojet engine. This remarkable feat by Sir Frank Whittle represents the birth of the turbine engine industry, which has greatly refined and improved Whittle's invention into the splendid engines that are flying today. During the past 50 years, the U.S. aeropropulsion industry has developed an enviable record in leading the world in the continual development of new aircraft engines with improved performance, durability, environmental compatibility, and safety. NASA, as did its predecessor NACA, takes pride in assisting the development of this record as a long-time partner with U.S. industry in the creation and development of advanced technologies which have spurred each new generation of engines.

This paper highlights some of the recent contributions of NASA's aeropropulsion research and technology efforts (fig. 1). Several technology advances that emerged from NASA research efforts in the 1970's and early 1980's were instrumental in the development of high-bypass turbofan engines that are powering today's fleet of commerical transports (such as the Boeing 767 shown at the lower left). And some of our more recent efforts have been key to the development of advanced turboprop engines which will lead to the introduction of a new generation of transports (center) in the mid-1990's. Also, we will describe some of the current research efforts that are aimed at advanced propulsion systems that might power transports in the 21st century. This includes advanced engines for both subsonic transports and high-speed transports such as the High-Speed Civil Transport (HSCT) and the National Aerospace Plane (NASP) (upper right).

Fifty years after the Whittle engine first ran, it is interesting to review the improvement in efficiency of commerical turbofan engines, shown in figure 2. The thermal efficiency of the Whittle engine was relatively low because of its low pressure ratio and low maximum temperature. As improved materials and aerodynamics became available, these parameters increased dramatically, improving the core thermal efficiency for first-generation turbine engines. Second- and third-generation turbine engines benefited from further increases in thermal efficiency and also obtained major improvements in propulsive efficiency by increasing the bypass ratio of the turbofan engine. Advanced turboprop engines will obtain further dramatic increases in propulsive efficiency by increasing the bypass ratio to its ultimate practical value.

NASA AEROPROPULSION CONTRIBUTIONS

Base Research and Technology Program

Base research and technology contributions of NASA's aeropropulsion program have been many and varied, and some of the more significant technologies are listed in figure 3. One of the most significant technology advances involved improved aerodynamic designs for fans and compressors. In the 1970's NASA, through both in-house and contract efforts, built and tested more than 100 single- and multiple-stage compressors and fans to develop and verify advanced design concepts such as high tip speeds, low source noise, controlled-diffusion blading, and low-aspect-ratio blading. These technologies were combined in the design of the compressors and fans of the Energy Efficient Engine Program, which provided unprecedented performance improvements. These components provide the basis for the fans and compressors on the newest commercial turbofan engines. The other major NASA contributions listed in figure 3 (composite materials and structures, thermal barrier coatings, reduced noise and emissions, and advanced controls) are described in later figures.

NASA Lewis Research Center has been a leader in the development of composite materials and the structural analysis necessary to provide significant reductions in engine weight and fuel usage (fig. 4). A PMR-15 polymer developed at Lewis is currently the nonmetallic composite matrix with the highest use temperature (550 to 600 °F). Composites using graphite fibers in a PMR-15 matrix have been used to produce a lightweight fan duct for the F404 engine, as illustrated on the left side of this figure. Current research is aimed at extending the use temperature to 800 °F. For higher temperatures Lewis is investigating metal and ceramic-matrix composite materials.

To efficiently use the anisotropic composite materials, new analytical methods and computer codes had to be developed. Composites micromechanics and laminate theories have been developed through Lewis programs and incorporated into the Integrated Composites Analyser (ICAN) code (right side of figure) to predict the material properties necessary to design components such as fan or propeller blades. These contributions have provided significant weight reduction and permitted improved aerodynamics through thinner blades without the dampers necessary on the older metal blades.

Ceramic thermal barrier coatings are being used in many of today's engines to extend the lives of metal parts used in combustors and turbines. The use of thermal barrier coatings by applying a ceramic coating onto a metal burner or turbine part to protect the metal and reduce its temperature was recognized in the 1960's. However, early applications were frustrated by the coating spalling off after short periods of use. NASA led research on those coatings which identified the failure mode as oxidation of the underlying metal and developed bond coatings and application procedures that have successfully prevented the coating failure. Increased reliability has resulted in the increased use of coatings in engines during the past two decades (fig. 5). Initial use was limited to a band-aiding approach to extend the life of combustor liners (left). During the 1980's improved thermal barrier coatings have been applied to selected areas, such as turbine vane platforms (center), to extend life and reduce cooling air requirements. As the technology of these coatings reaches full maturity, thermal barrier coatings will be extended to more critical areas, such as the aerodynamic surfaces of turbine blades (right).

NASA has played a dual role in noise reduction of commerical turbine-powered aircraft by contributing to the technology and by providing unbiased expert consulting to the FAA in its rule-making role. This role, combined with industry programs, has resulted in dramatic reduction in noise generated by the modern turbofan aircraft (fig. 6), making them the good neighbors they are today. NASA Lewis did extensive research in the sources of noise, acoustic treatment to suppress the emitted noise, and necessary procedures to measure noise in ground test facilities so that flight noise could be estimated. This understanding was used by NASA and the industry to design new components, engines, and installations that reduced airport noise to an acceptable level.

The trend in turbine engines toward more controlled variables to get improved performance and efficiency, as shown in figure 7, has made it necessary to switch from the old reliable hydromechanical control to a modern, flexible digital control. The many technical barriers to this transition have been a subject of research at Lewis since a J-85 engine was first operated under digital control in 1970. To develop a formalized procedure to design controls for so many simultaneous variables, multivariable control theory for turbine engines was developed by Lewis and demonstrated in the F100 Multivariable Control Program. Since the most unreliable components of the control are the engine sensors, Lewis developed algorithms to allow the failure of sensors to be detected and accommodated while continuing to safely control the engine. Digital control is currently being used on the F100 in a supervisory trimming mode with a hydromechanical control and is being demonstrated in flight in a full authority mode in the digital electronic engine control (DEEC) for the F100 engine. This type of control system will be on most of the new high-performance engines of the 1990's and 2000's.

Advanced Turboprop Program

The effect of bypass ratio on civil transport engines in terms of fuel usage is shown in figure 8. The specific fuel consumption (SFC) of turbine engines has declined as the bypass ratio has been increased. When turbine engines were first introduced in commerical service, they were a great success as long as the fuel price was very low. To improve fuel efficiency, the bypass ratio was first increased to about 2 for the low-bypass engine and finally to about 7 for the high-bypass engines with resulting large decreases in SFC. When the fuel crisis hit in the mid-1970's, it became apparent that further decreases in SFC were very desirable. Therefore, the further reduction in SFC available with the ultimate in high bypass, the propeller, was recognized as a goal worth investigating.

As a result of earlier turboprop experience, it was initially difficult to get the reintroduction of propellers for propulsion of commercial aircraft taken seriously. To compete with turbofan aircraft, similar speed and cabin comfort were required. Therefore, as shown in figure 9, the initial research at Lewis in the late 1970's was aimed at demonstrating desirable performance and noise at higher cruise speeds than had previously been obtained with propellers. The success of this research indicated the feasibility of achieving major reductions in fuel usage with advanced propellers. However, studies and analyses indicated that the full turboprop system had to be demonstrated in flight tests. So research in mechanical systems, such as gearing and pitch-change mechanisms, and propulsion integration were initiated in the early 1980's. While single-rotation propeller systems are simpler and have application to many types of aircraft, it was recognized that the swirl loss of about 8 percent could be avoided with counterrotation. The additional benefit of propulsion integration on aircraft with tail-mounted engines further increased interest in counterrotation so that research was started in the mid-1980's. These programs have culminated in flight demonstrations of the technology by Lockheed on a Gulfstream II, by Boeing on a 727, and by McDonnell Douglas on an MD90. NASA has been actively involved as a partner in all of these flight tests.

The Advanced Turboprop Program has included NASA in-house research in both experimental and analytical aerodynamic, acoustic, and structural technologies. These programs have contributed to the understanding of flutter, acoustics, and aerodynamics of swept transonic propeller blading. Some recent results, shown in figure 10, represent Euler solutions of the flow over the blades. At low forward speeds the leading-edge vortex system displayed in the left picture explains the good aerodynamic performance not predicted by the simpler two-dimensional aerodynamics. Unsteady Euler solutions predict the time-varying propeller aerodynamic forces obtained at angle-of-attack (shown in the center picture), and the unsteady forces on the blades in a counterrotation propeller system (shown in the right picture).

As a result of ongoing successful flight programs demonstrating the advanced turboprop technology, applications will be following in the near future. As the price of fuel inevitably increases, the increased efficiency of turboprop systems will be even more attractive, and transport aircraft such as the proposed Boeing 7J7 and McDonnell Douglas MD93 should become production aircraft. Advanced cargo aircraft, such as shown in figure 11, are being considered to provide improved range and efficiency and to replace military aircraft such as the C141 and the C130.

Hot Section Technology (HOST) Project

In the early 1980's, the life of commercial engine hot sections was considerably shorter than desired. NASA's HOST Project was conducted to focus technologies for aerothermodynamic and structural analysis of combustors and turbines toward more accurate predictions of hardware life (fig. 12). Therefore, for the first time, the aerothermodynamics to predict the thermal environment, heat transfer, and resulting thermal loads on components were combined with materials behavior to predict the structural response and resulting life. Before the HOST Project, life prediction was a primarily empirical art; if a new component differed significantly from previous experience, life prediction was inaccurate and ultimately dependent on life testing and redesign if problems arose. HOST has combined the analytical approach with the development of advanced instrumentation used in benchmark quality experiments to better characterize the actual hot-section environment and to verify computer codes. As a result, more accurate analytical predictions of hot-section life are now possible.

The HOST instrumentation program focused on two types of instrumentation: instrumentation for characterizing the environment in the hot-section region and instrumentation for measuring the effect of that environment on the hot-section components. Examples of each type are shown in figure 13. The thermocouple probe is capable of measuring dynamic gas temperature fluctuations with a frequency response out to 1000 Hz. Tests of this probe at the combustor exit of an F-100 engine showed rapid dynamic gas-temperature excursions from as low as the compressor-exit temperature to near stoichiometric temperatures. The lower left picture is a view of a fuel nozzle in an engine operating at full power, obtained by using the new fiber optic combustor viewing system. Not only can it get such views in an operating engine for the first time, but by using laser light as an illumination source and filtering out the combustion-generated light, it can look through the flame and view the opposite wall during operation. Heat flux measurement on an operating turbine vane is another new capability developed in the HOST Project. These and other new instruments are giving new understanding of the environment in the hot sections of operating turbine engines.

Predictions of the HOST codes for a turbine blade in an operating engine are illustrated in figure 14. The variation of load with time associated with engine operation during a typical flight is shown in the upper left of the figure. The aerothermodynamic codes are used to predict the mechanical and thermal loading on the blade shown in the upper right. Heat-transfer codes are used to predict the temperature distribution in the blade, as shown in the lower left, at each instant of time. Mechanical and thermal loading distributions are used in structural analysis codes to determine the stress and strain distributions in the turbine blade. By evaluating the time-varying stress and strain using a life model, failure can be predicted; in this case, at about the center of the blade leading edge. Understanding the failure mechanisms in this manner allows a designer to correct life-limiting parts before the engine runs for the first time.

TURBINE BLADE MATERIALS TRENDS

From the beginning of the turbine engine in the 1930's, the materials have limited its efficiency and maximum thrust. In the 1950's and 1960's turbine blade materials were first wrought and later conventionally cast. During that period, use temperatures increased at a moderate pace (fig. 15). Beginning in the 1970's, new materials processing methods accelerated the pace at which use temperature increased. During this period, Lewis developed oxide-dispersion-strengthened (ODS) superalloys in-house and through contracts, and subsequently spun off the technology to industry to provide commercial alloys. The 1950's Lewis experience with tungsten-fiber-reinforced superalloys has been recently used to manufacture the first silicon-carbide-fiber/titanium-aluminide-matrix composite material and to characterize it. These materials, combined with Lewis-developed thermal barrier coatings, will provide surface use temperatures up to 2300 °F in the 1990's. The Advanced High Temperature Engine Materials Program, beginning this year, will develop materials like the silicon-carbide-fiber/reaction-bonded-silicon-nitride material identified in the Lewis in-house program for use in the 21st century at temperatures of 2500 °F and higher. These new materials, through new higher values of use temperature, provide the opportunity of reaching new heights in turbine engine efficiency and thrust at speeds from subsonic to high supersonic if the accompanying aerodynamic and structural technologies can also be developed to allow maximum use of the material capabilities.

FUTURE COMMERCIAL SUBSONIC ENGINES

Returning to figure 2, which shows the historical increases in efficiency obtained in commercial engines, the future gains obtainable with the full potential of advanced technology have been added to identify the ultimate goal for subsonic engines (fig. 16). The left portion of the goal corresponds to advanced turbofans and the right portion to the turboprop with its higher propulsion efficiency. Reaching that goal requires new levels of performance from all the engine components by integrating the advanced technology in materials, aerodynamics, and structures.

The effect of overall pressure ratio on core thermal efficiency is shown in figure 17 for several levels of maximum cycle temperature and whether the hot-section components are cooled. For current component capabilities of 2300 °F with cooling, there is only a minor benefit with increasing pressure ratio. However, if the components could be operated uncooled at 2300 °F (with improved materials), significant increases in efficiency could be obtained if the pressure ratio of the core was increased to 60 or more. In addition, if advanced components with improved aerodynamic efficiency were available, further increases in thermal efficiency could be obtained at 2300 °F if the pressure ratio was further increased to 100. Increasing advanced component operating temperature to 3000 °F uncooled (with ceramic and carbon/carbon components) requires even higher pressure ratios to obtain maximum efficiency. It is important to note that increased temperature must be combined with more efficient components and unprecedented levels of cycle pressure ratio in order to realize major increases in core efficiency.

The core pressure ratios necessary to realize the full potential of new materials will require new aerodynamic technology for both the high compressor and turbine. As shown in figure 18, at pressure ratios of 100 or more, new materials will be needed in the latter stages of the compressor where the temperatures reach 1600 °F and higher. These last stages will also have very low corrected weight flow and the minute passage heights characteristic of small engines. Since small engines (with centrifugal/radial flow components) have had relatively low performance when compared with commercial turbofan engines, NASA has been directing significant effort at understanding the loss mechanisms associated with these components and developing technology to minimize these losses. Thus, our small-engine technology efforts might well play a key role in the future development of improved large engines.

As part of our research efforts for small engines, we are currently assembling a large-scale, low-speed centrifugal compressor to investigate the internal three-dimensional flows so that they can be understood and controlled with resulting efficiency improvements. The rotor, shown in figure 19, is 5 ft in diameter and large enough to install instrument rakes in the passages and to instrument the vanes and walls with static pressures. The casing is also constructed with access for laser anemometry to document the interior flow fields. Analytical codes are being developed in parallel with the experimental efforts. The left figure illustrates the initial results of a quasi-three-dimensional thin-layer analysis which represents the expected flow on the meanline of the passage. Results of this research should eventually lead to improved performance of centrifugal compressors for use in small engines or the latter stages of large commercial engines.

Another element in our small engine technology efforts involves ceramic, uncooled, radial-flow turbomachinery. For several years Lewis has managed the Automotive Gas Turbine Program for the Department of Energy. The major emphasis of this program is to advance the technology of ceramics to a point where these brittle materials can be considered as serious candidates for use in high-performance turbomachinery. The goal of this program is to produce and demonstrate ceramic components capable of operation in a small-engine environment at temperatures of 2500 °F. Significant progress has been made. Fabrication technology has progressed from the manufacture of simple test bars and laboratory specimens to engine quality, complex parts, as shown in figure 20. Static parts, like those in the figure, have been rig tested at the target temperature of 2500 °F for extended periods. All the ceramic parts, including the turbine rotor, have been demonstrated in an engine at 2200 °F for 85 hours at 70 percent of design speed. A turbine rotor has been tested in an engine at 1950 °F and 100 percent of design speed for several hours. Future work is aimed at component reliability through improved materials, design, and manufacturing techniques to increase the overall reliability of ceramic engine components.

In addition, Lewis has NASA-sponsored research efforts aimed at extending the use temperature of ceramics to 3000 °F with life similar to current engines. Thus, emphasis is on high-temperature use of ceramics and on their structural and environmental durability and reliability. The program is interdisciplinary in nature with major emphasis on materials and processing and significant efforts in design methodology and life prediction.

LONG-RANGE, HIGH-SPEED FLIGHT

While NASA Lewis will continue to work on subsonic propulsion technology, the major part of its aeropropulsion program is shifting toward propulsion systems for long-range supersonic and hypersonic aircraft (fig. 21). The bottom picture represents configurations being studied for second-generation commercial supersonic transports that will probably be limited to turbine engine propulsion and hydrocarbon (JP-type) fuels. The Mach 5 military aircraft in the center of the figure is a configuration that Lewis has been investigating jointly with Langley Research Center and represents aircraft that cruise at speeds beyond those possible with turbine engines and hydrocarbon fuels. Lewis is also heavily involved in technology maturation efforts for propulsion systems being considered for the National Aerospace Plane Program represented by the aircraft in the upper left of the figure. The NASA aeropropulsion program will study propulsion systems for these aircraft to provide technology for improved efficiency, specific thrust, and environmental compatibility.

Most of the propulsion concepts under study at NASA for high-speed flight are shown in figure 22. Many of them have turbine engine hardware in the prime propulsion stream, but some nonturbomachinery systems are being studied for special applications, such as acceleration missions (for example, the air liquefaction cycle and scramjet cycle). High-speed cruise missions usually use turbine engines for acceleration and cruise, unless the cruise temperature is excessive for the engine. In these very high speed cases, either ramjet or scramjet propulsion is used in a dual cycle. For supersonic cruise of a commercial transport, NASA, in a joint program with industry, is studying many turbine engine cycles, including the turbofan with a supersonic-throughflow fan which appears to be a promising new concept.

High-Speed Civil Transport

Returning to the efficiency figure (fig. 2), a supersonic cruise aircraft goal has been added (fig. 23). Because of the large ram-pressure-ratio in supersonic flight, the Concorde propulsion system achieves a relatively high overall efficiency in spite of its 1960's technology. However, at the termination of the NASA Supersonic Cruise Program in the early 1980's, variable-cycle engines for supersonic cruise were estimated to offer a significant increase in efficiency over the Concorde engine's value of 40 percent. The goal of the current NASA program is to increase that efficiency to at least 60 percent through the use of advanced materials, structures, aerodynamics, and cycles like the one using a supersonic-throughflow fan.

Supersonic Throughflow Fan Technology

The advantages of the supersonic fan relative to a baseline afterburning turbofan are illustrated in figure 24. The simpler inlet and fan are lighter weight and more efficient by avoiding the complexity of slowing the external flow to subsonic speeds before introducing it to the fan. These advantages provide about a 10-percent decrease in specific fuel consumption and about a 25-percent reduction in propulsion weight, which leads to a 22-percent increase in aircraft range. Since the feasibility of maintaining supersonic flow through a turbomachinery stage has never been demonstrated, Lewis has initiated an exploratory program to investigate the feasibility of the supersonic fan component.

A cross section of the supersonic fan experimental hardware currently being constructed at Lewis is shown in figure 25, together with several computer solutions used in its design and analysis. The supersonic fan rotor and stator are located in the center of the installation downstream of an annular sliding block nozzle, which generates the supersonic flow into the rotor. A similar sliding nozzle is located downstream of the stator to slow the flow before it enters the exhaust duct. The quasi-three-dimensional thin-layer Navier-Stokes solution shown on the left was used to optimize the pressure distribution on the blading in the presence of the blade boundary layer. The analytical results shown at the bottom of the figure illustrate the unsteady interaction between the rotor and stator flow fields. The analytical results are processed to look like a schleiren photograph of the flow.

Very High Speed Propulsion

As we direct attention to higher speed regimes, hybrid propulsion systems beyond turbomachinery cycles must be considered. Figure 26 presents the specific impulse of the basic airbreathing propulsion cycles and compares them with the best rockets. The cycles with turbomachinery provide the highest specific impulse at speeds up to about Mach 5 where it becomes too hot for the turbomachinery to produce enough pressure ratio to overcome the inefficiency of its components. The subsonic ramjet then provides the highest specific impulse until about Mach 10 where molecular dissociation reduces its impulse below that of the scramjet. Airbreathing cycles always have a higher impulse than rockets but are much more difficult to operate at the higher Mach numbers. Work at Lewis and other NASA centers is aimed at extending the use of airbreathing cycles to Mach numbers higher than the Mach 3+ flown by the YF12.

A joint study of a military Mach 5 cruise aircraft by Lewis and Langley Research Centers and industry partners identified an over/under turboramjet cycle to provide desirable acceleration and cruise performance. The Mach 5 inlet illustrated in figure 27 represents the ramjet configuration with the turbine engine compartmented off for high-speed cruise. The experimental inlet hardware was recently delivered to Lewis for test in the 10- by 10-Foot Supersonic Wind Tunnel. Results of a fully viscous three-dimensional analysis displayed in the figure indicate that the sidewall boundary layer will collect on the cowl side of the inlet sidewall and cause separation, which would probably cause inlet unstart. Analytical results such as these were used to design a bleed system for the experimental hardware that will be tested in the near future.

While supersonic combustion ramjets (scramjets) were envisioned over 20 years ago, no one has yet proven their practical use. Langley has led NASA's scramjet propulsion research and recently demonstrated positive thrust on a scramjet configuration similar to the one shown in figure 28. Similar work is now planned by the NASP contractors, as the successful operation of the scramjet cycle is necessary to achieve a single-stage-to-orbit vehicle. The environment of a scramjet module is extremely hot and can be created in test facilities on the ground for only a few minutes at Mach numbers up to 10. Therefore, scramjet operation at higher Mach numbers will be critically dependent on computational fluid dynamics for analyzing and designing future scramjet configurations.

CONCLUDING REMARKS

The U.S. aeropropulsion industry has been very successful in competing in the world market for powering modern aircraft. NASA takes great pride in its contributions to that success, some of which have been reviewed in this paper. As the world competition grows, it will become harder to maintain our current leadership. NASA's current aeropropulsion program will continue to support that leadership by emphasizing technology that will provide future opportunities for major advances in propulsion efficiency and durability. While we have reviewed the highlights of that program, we could not cover it in sufficient detail nor describe enough of its programs to gain a full appreciation of its breadth and scope. Also, we have primarily concentrated on propulsion technology for commercial aircraft applications; however, much of NASA's propulsion technology advances are also applicable to military aircraft systems. The papers that follow will provide a broader description of the NASA aeropropulsion program, which should help lead the industry into continuing to produce the best propulsion systems for commercial and military aircraft into the 21st century.

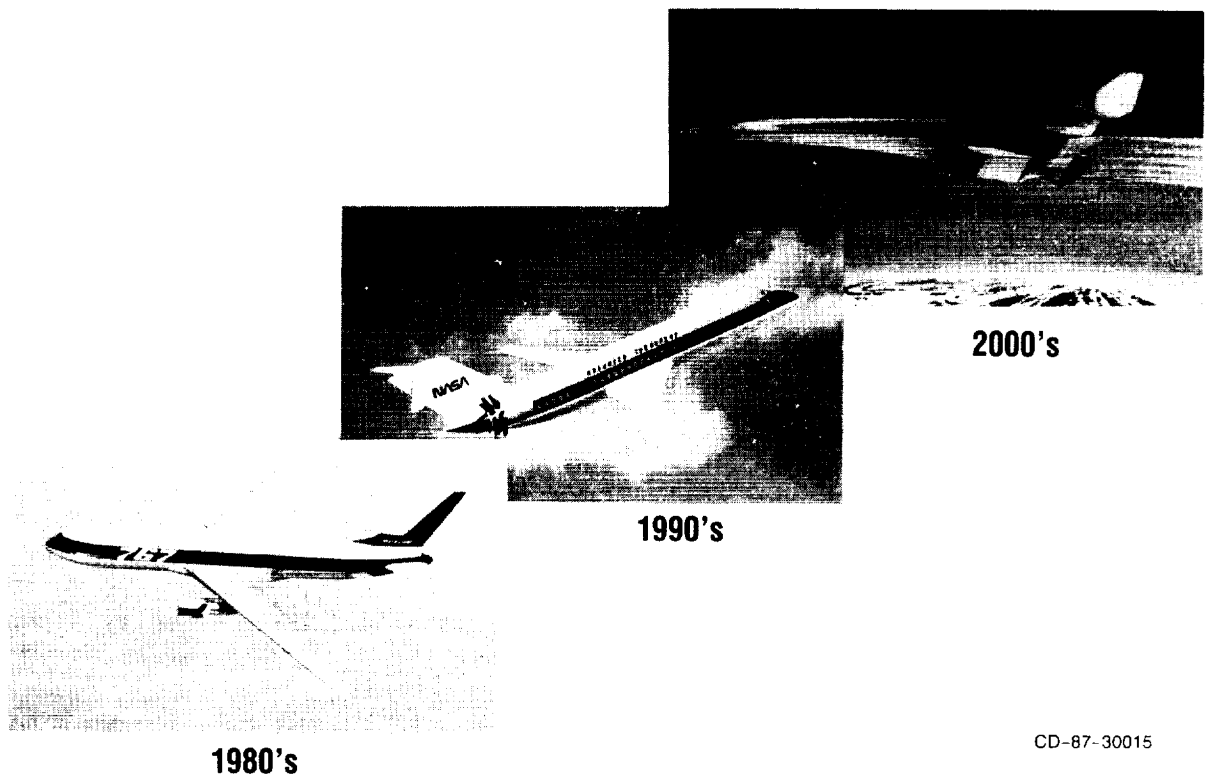

Figure 1. - Current and future aircraft benefiting from NASA's Aeropropulsion Technology Program.

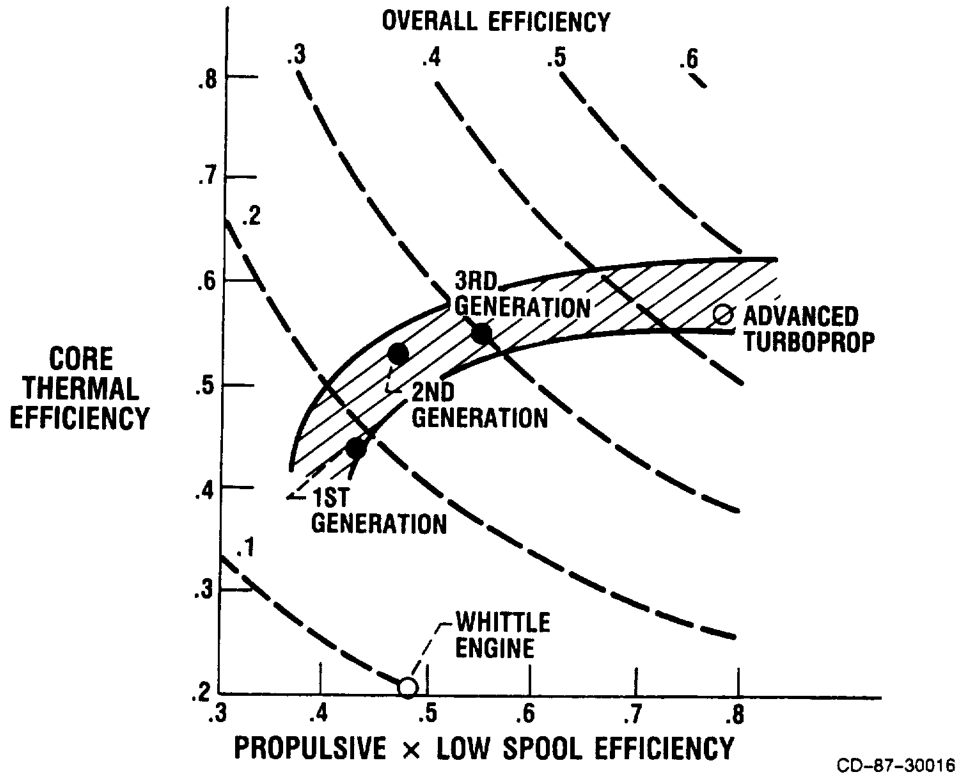

Figure 2. - Efficiency trends for commercial subsonic turbine engines.

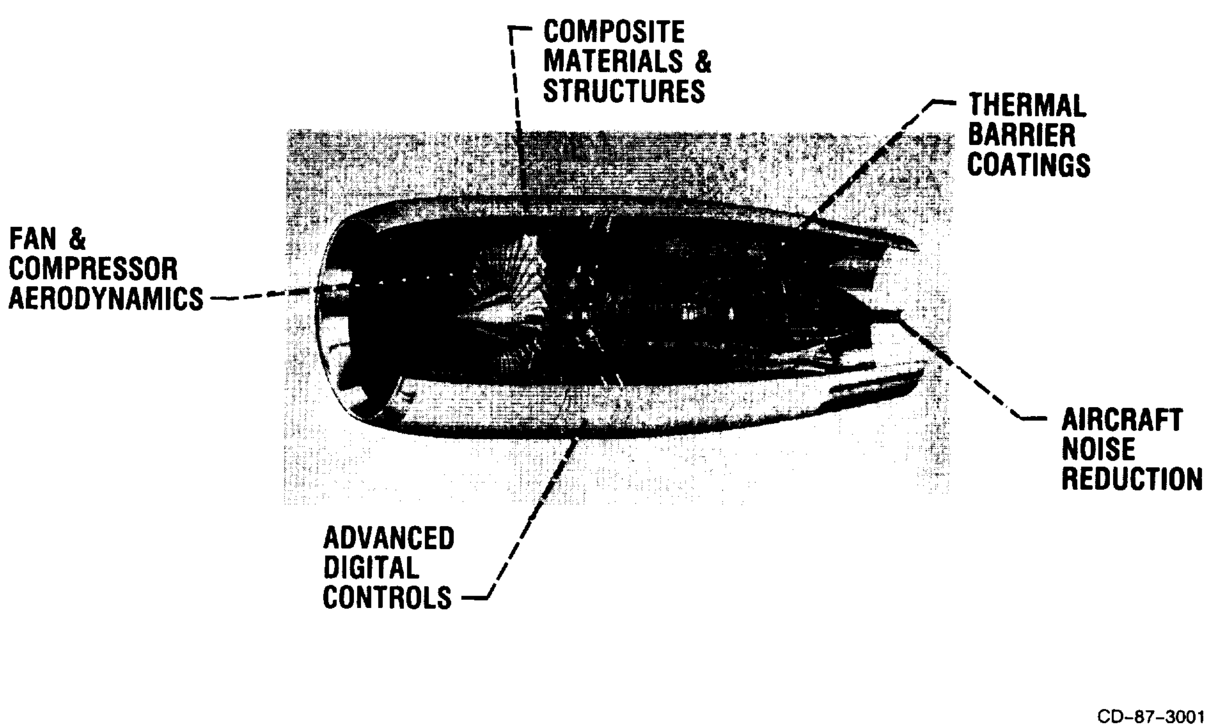

Figure 3. - Contributions to modern turbofan engines from the NASA Lewis aeropropulsion program.

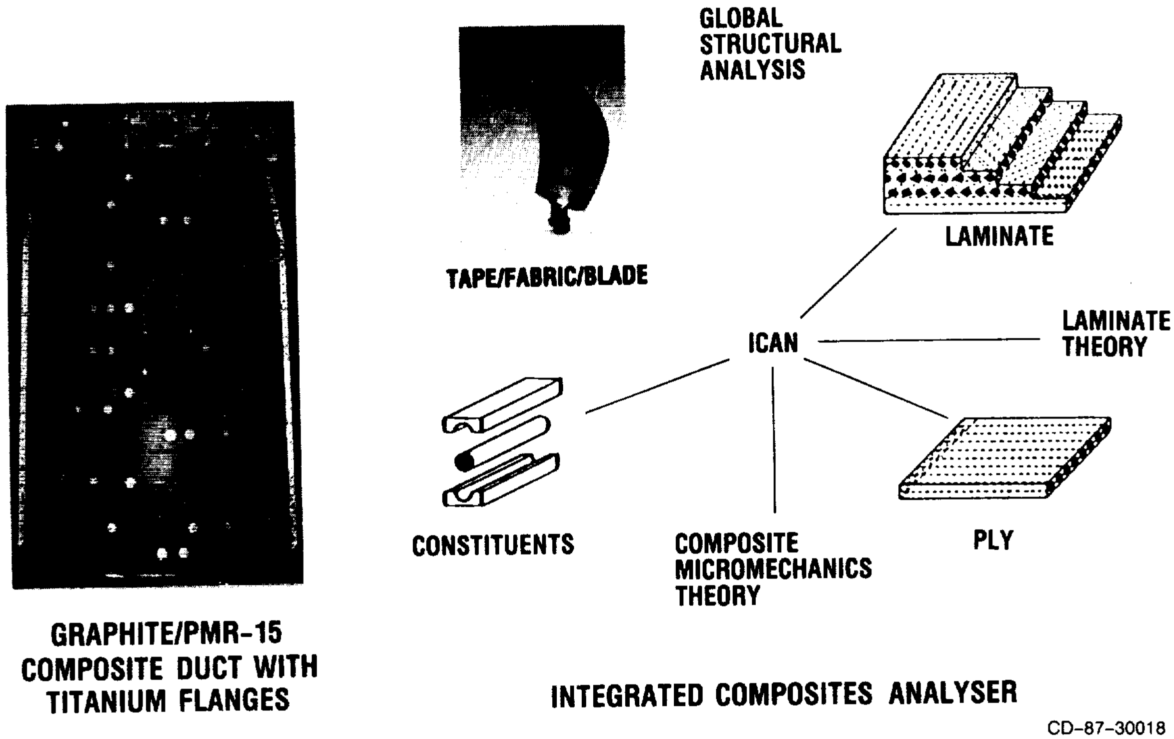

Figure 4. - Contributions of the Lewis aeropropulsion program to advanced composite materials and structures technology in modern turbine engines.

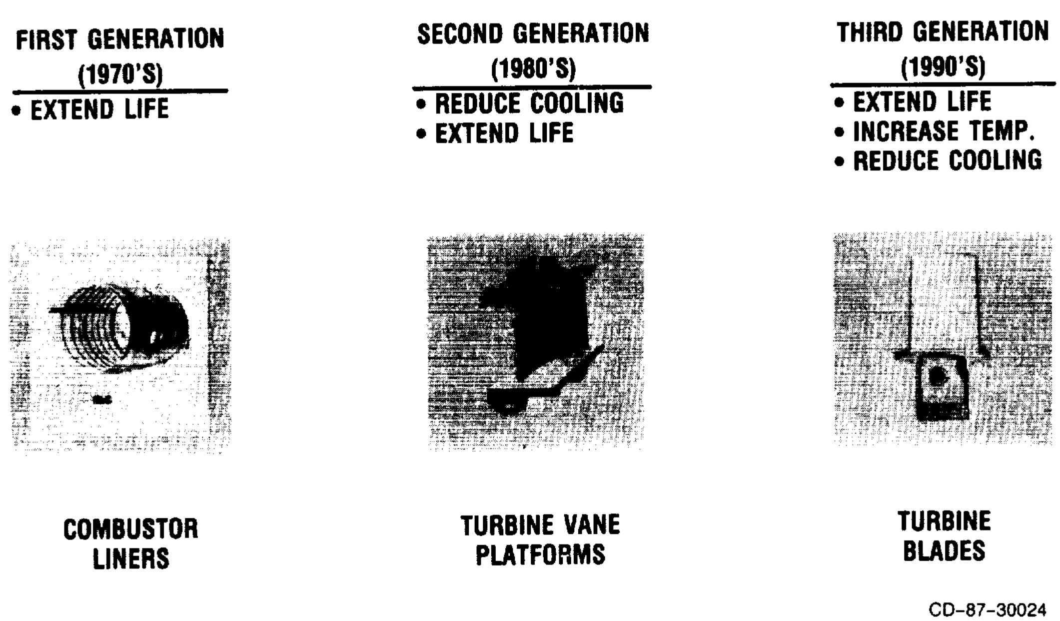

Figure 5. - Applications for Lewis thermal barrier coating technology.

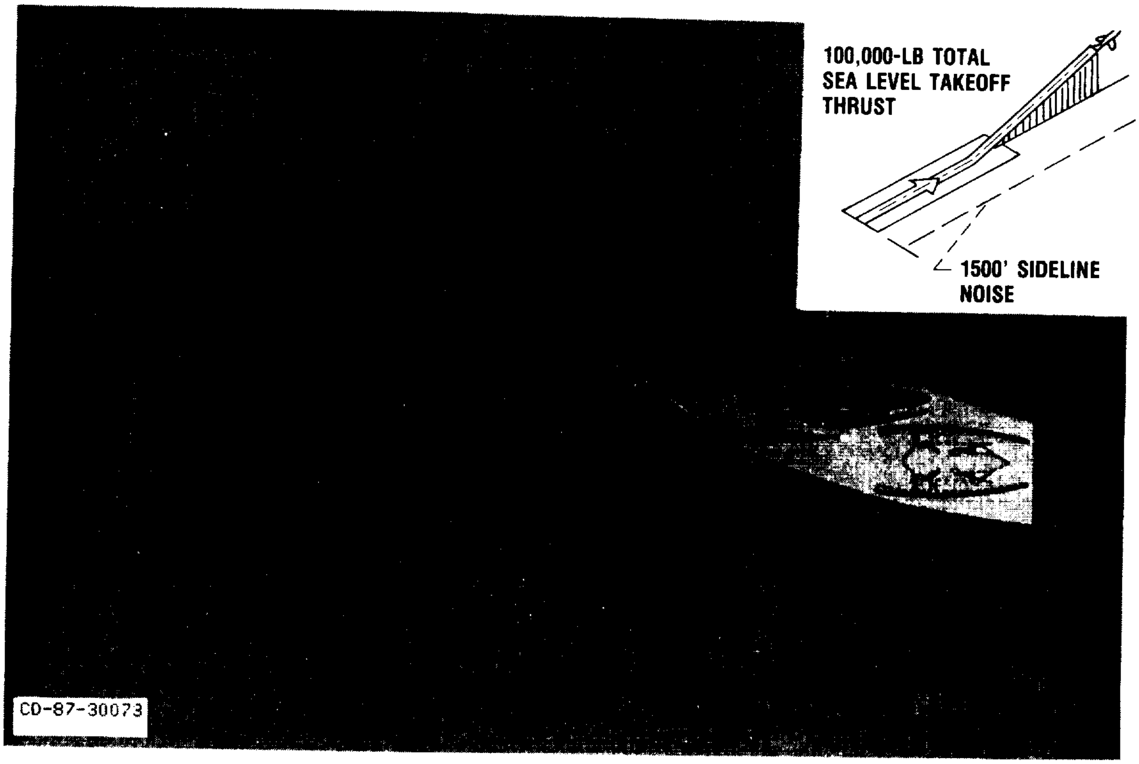

Figure 6. - Historic aircraft noise reduction due mainly to advanced aeropropulsion technology.

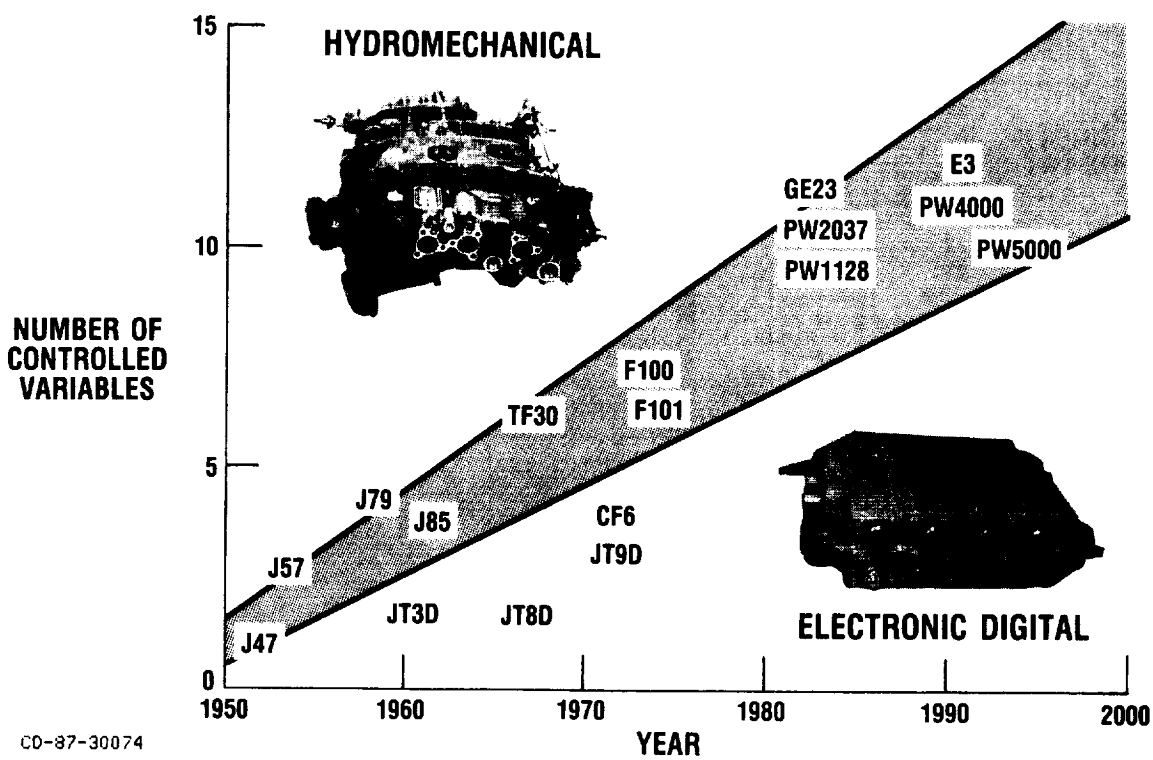

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Figure 7. - Advanced electronic digital controls provide unprecedented flexibility and capacity for increasing the number of controlled turbine engine variables.

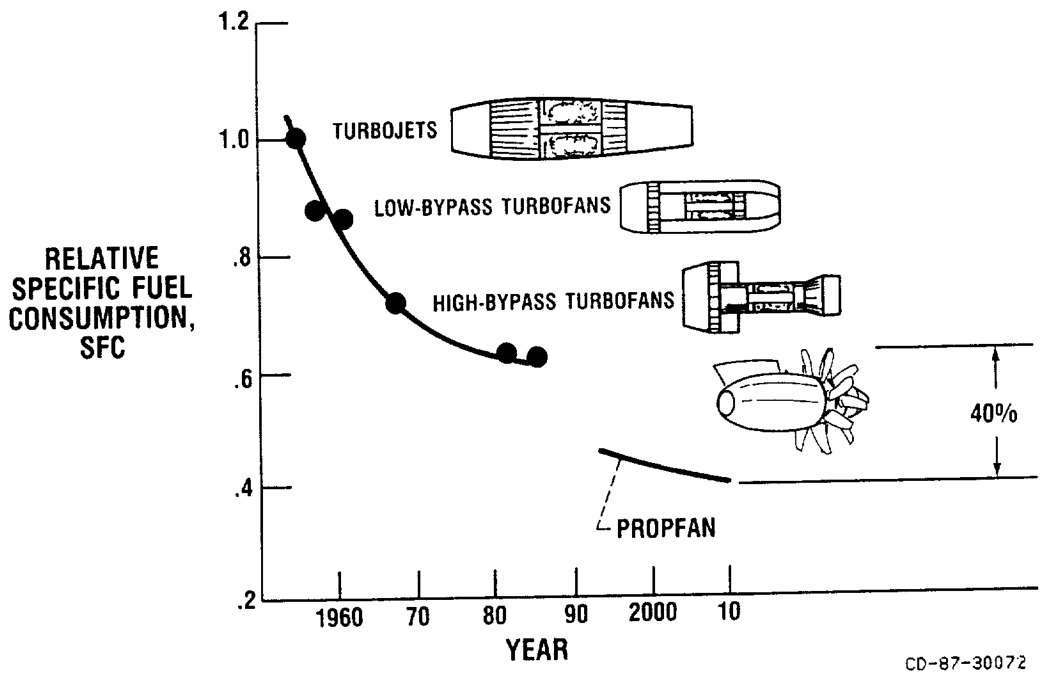


Figure 8. - High-bypass engines have better subsonic performance.

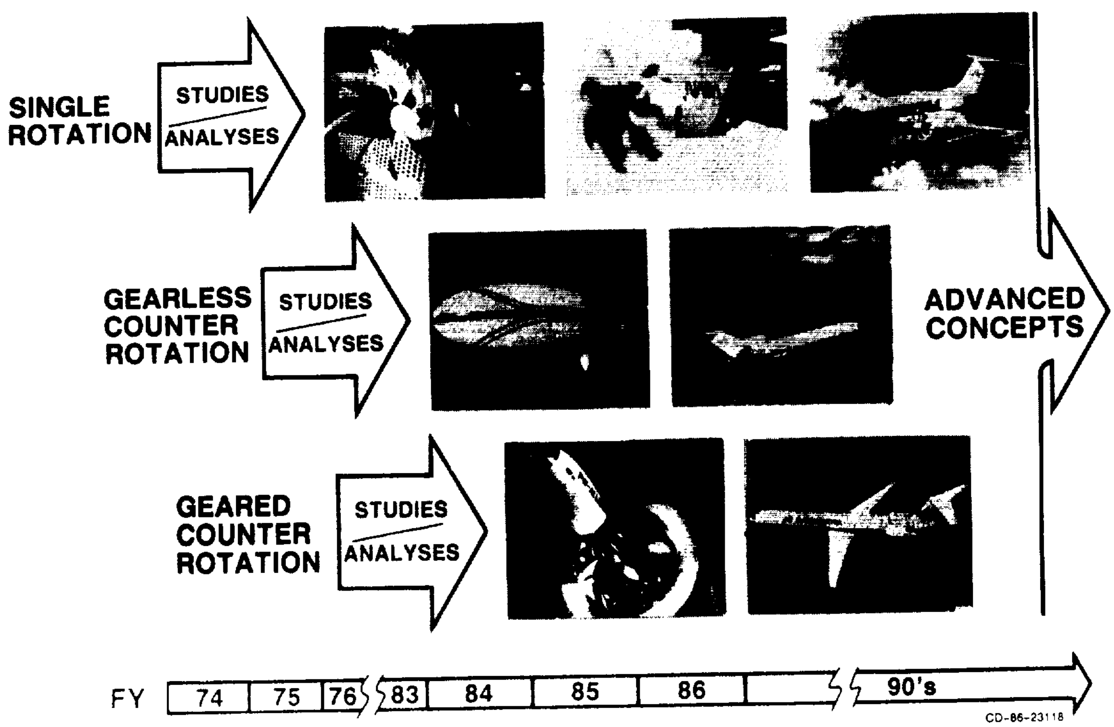
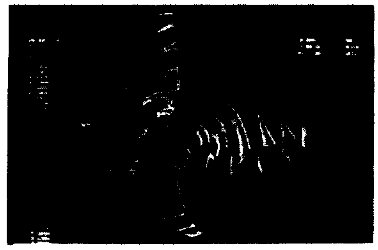


Figure 9. - Advanced Turboprop Program.



LEADING EDGE VORTEX AERODYNAMICS AT LOW SPEED

UNSTEADY AERODYNAMICS AT ANGLE OF ATTACK

UNSTEADY COUNTERROTATING BLADE ROW INTERACTIONS

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Figure 10. - Advanced computational fluid dynamics analysis for propeller flow fields.

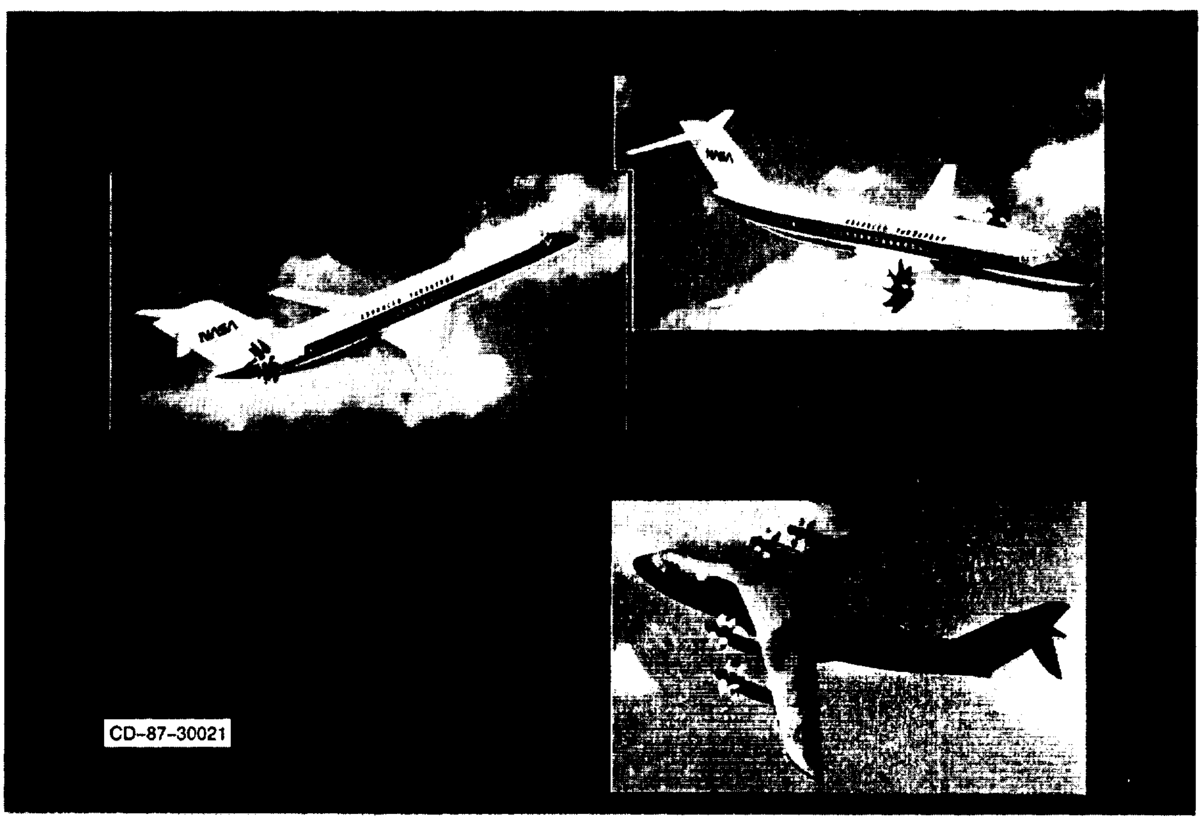

Figure 11. - Potential future advanced turboprop applications.

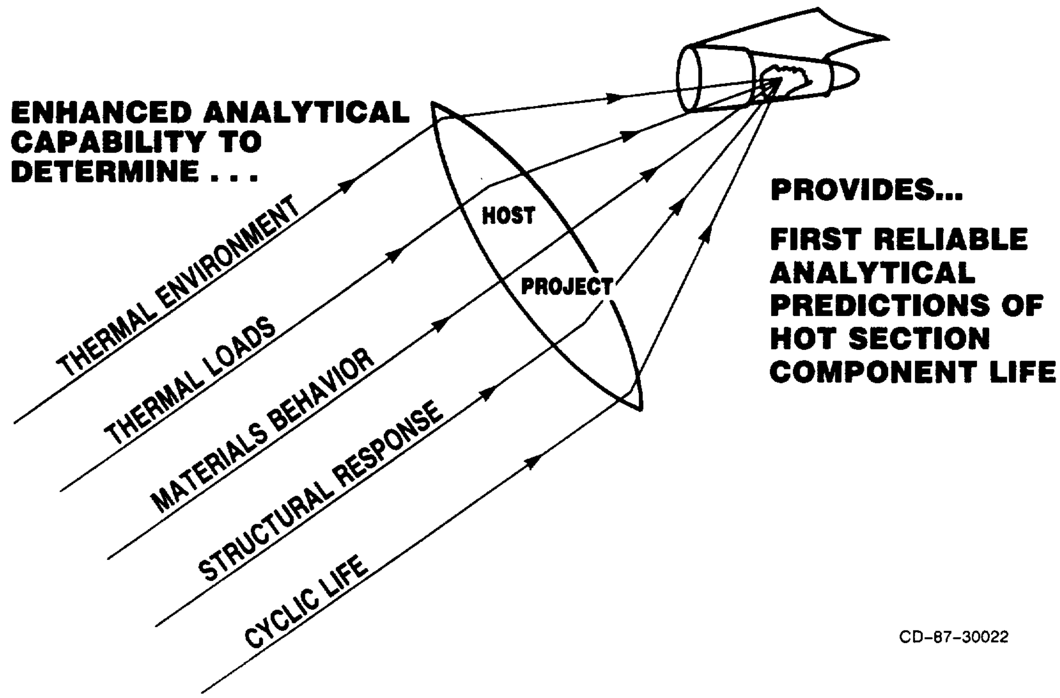

Figure 12. - NASA's Hot Section Technology (HOST) Project.

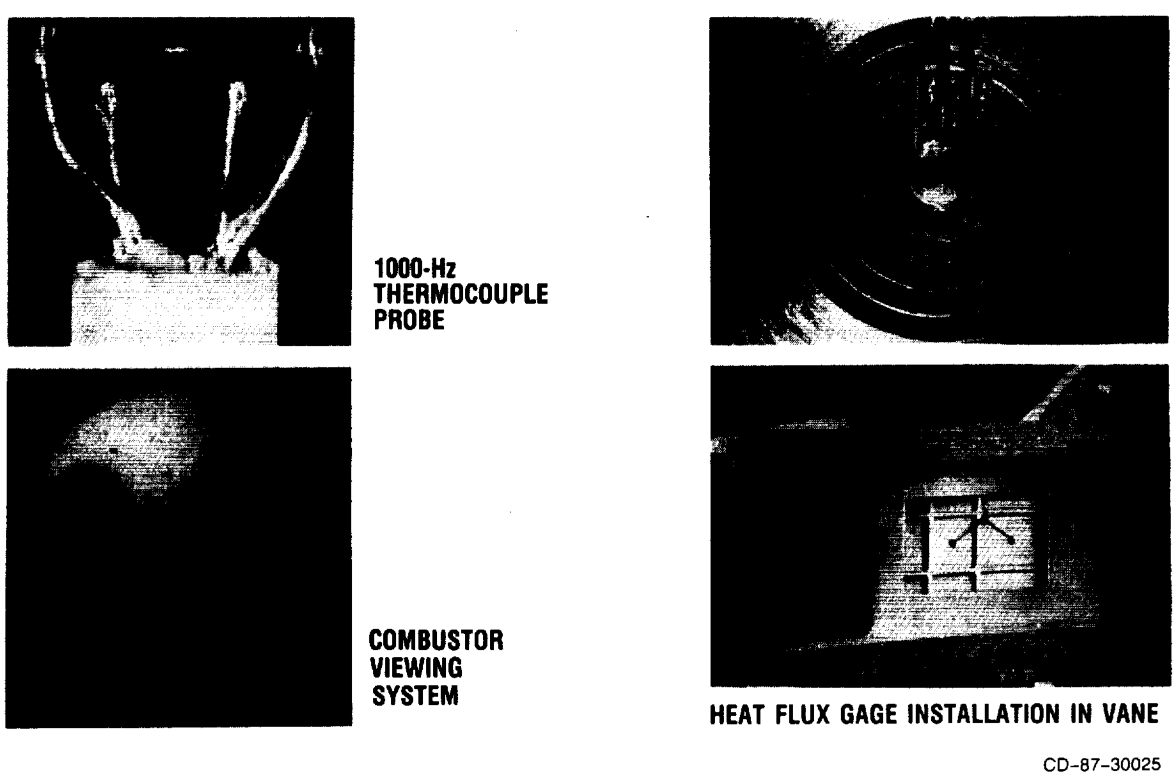

Figure 13. - HOST project instrumentation technology.

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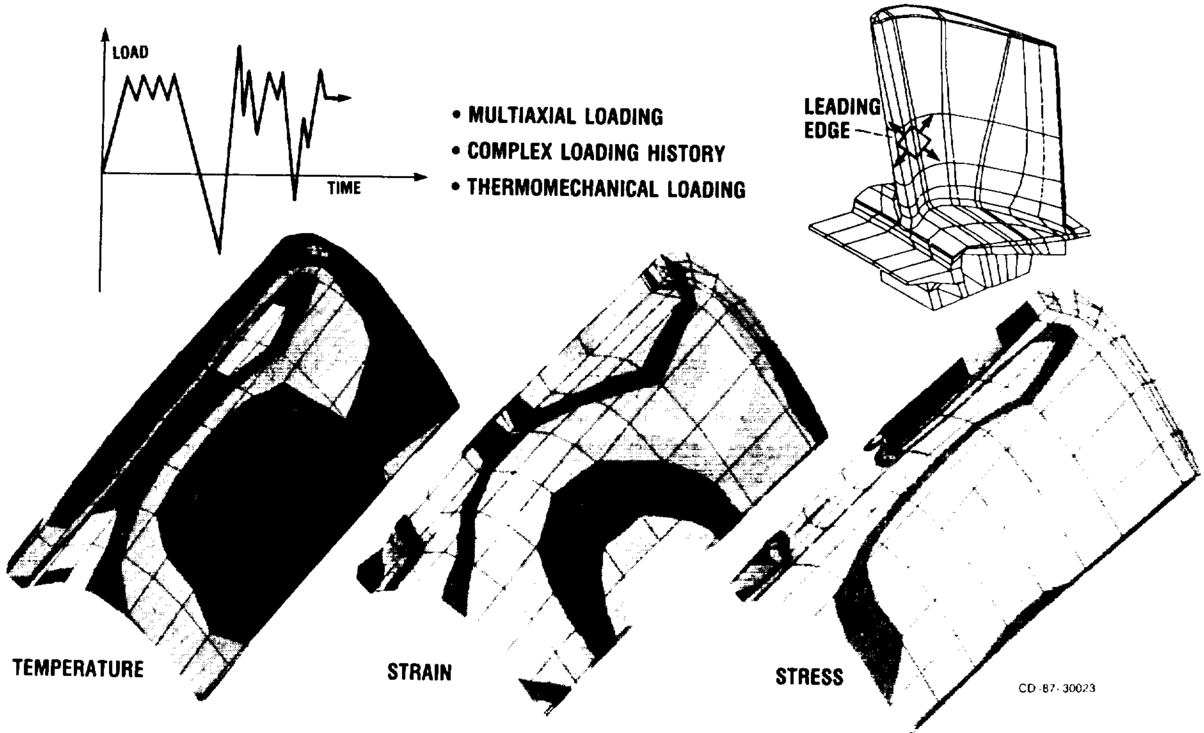

Figure 14. - HOST prediction of operating conditions and life.

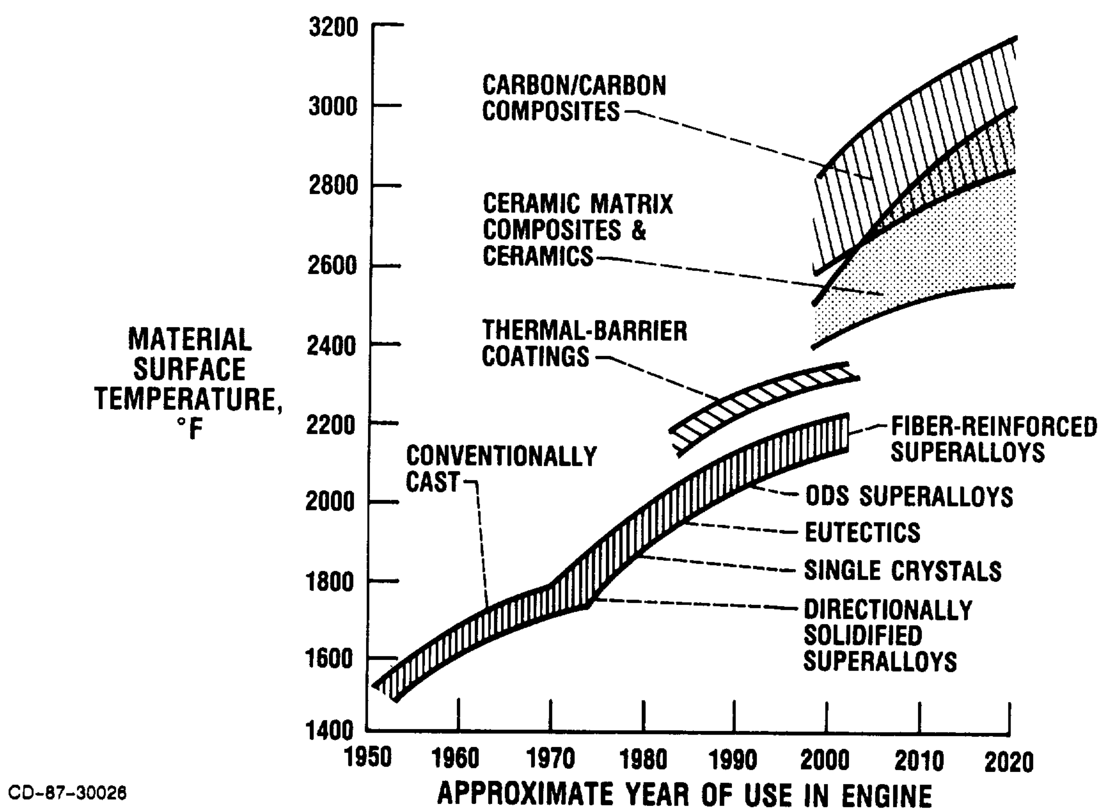

Figure 15. - Historic and projected turbine blade materials trends.

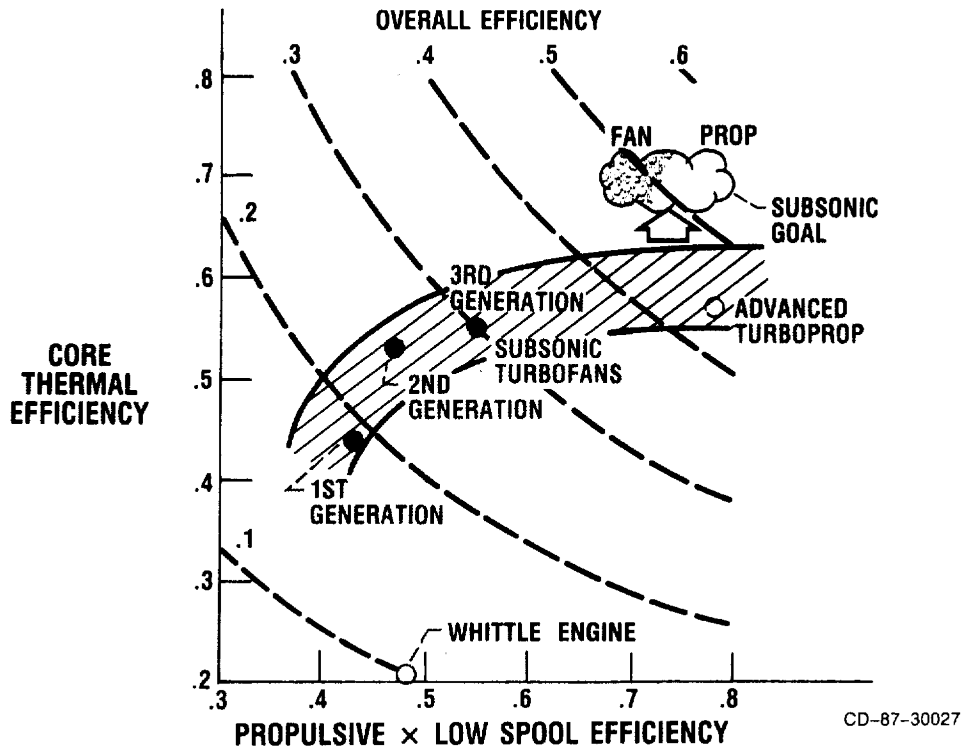

Figure 16. - Goal for future commerical turbine engine efficiency.

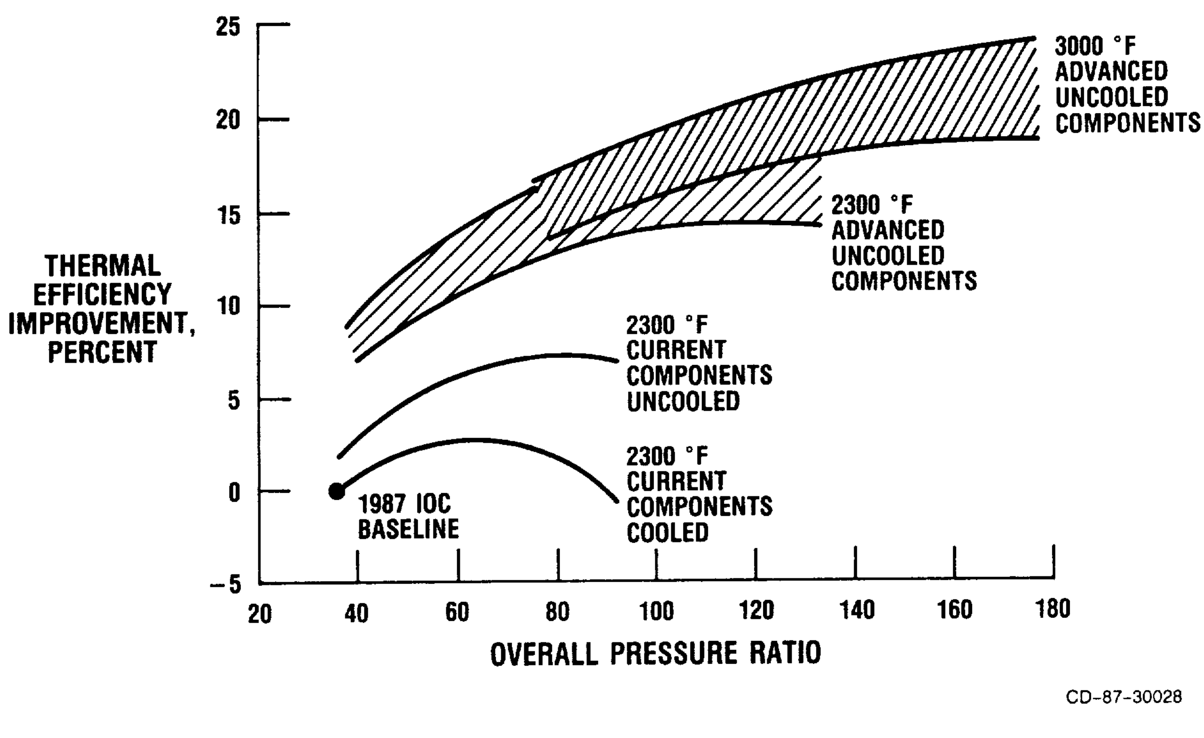

Figure 17. - Core technology effect on turbine engine thermal efficiency.

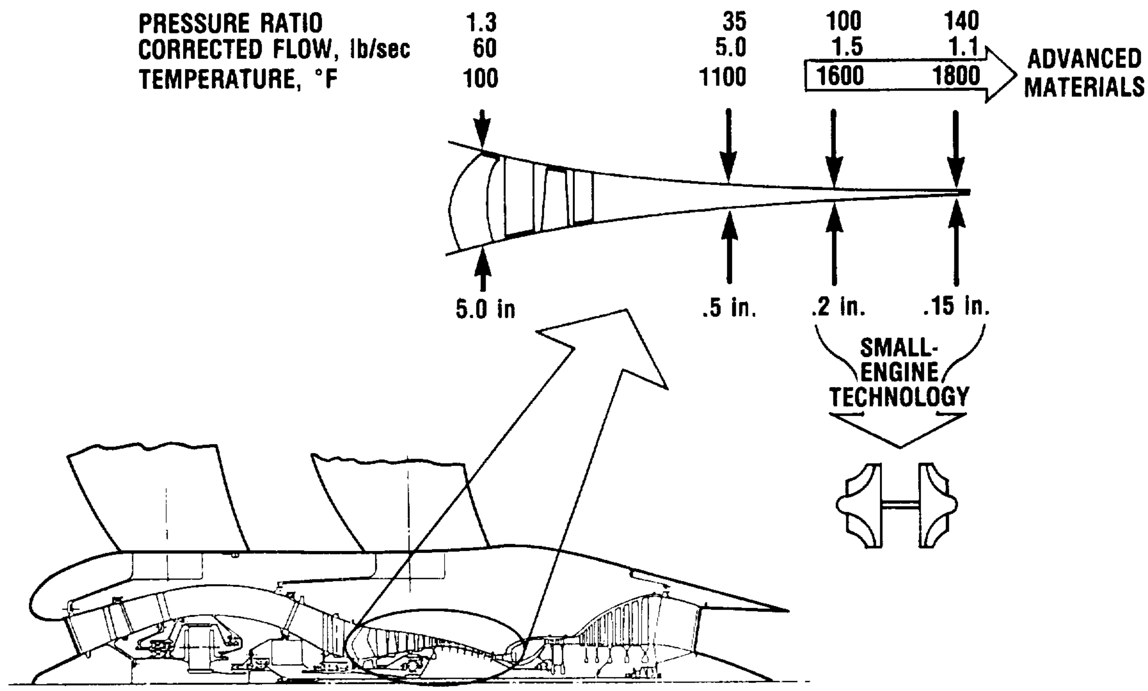

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Figure 18. - Impact of very high core pressure ratio on required compressor technology.

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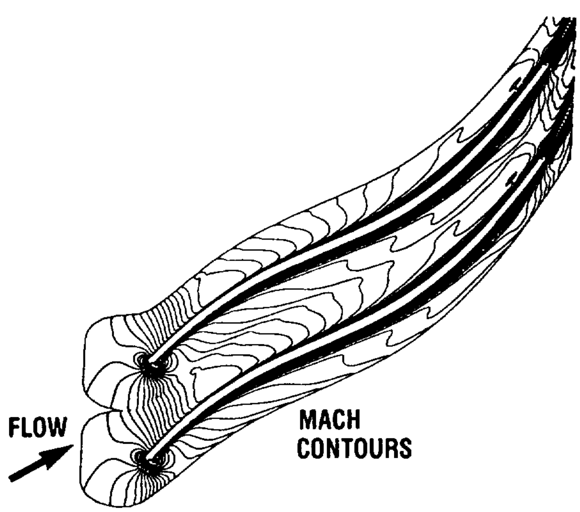

QUASI-3D THIN-LAYER ANALYSIS

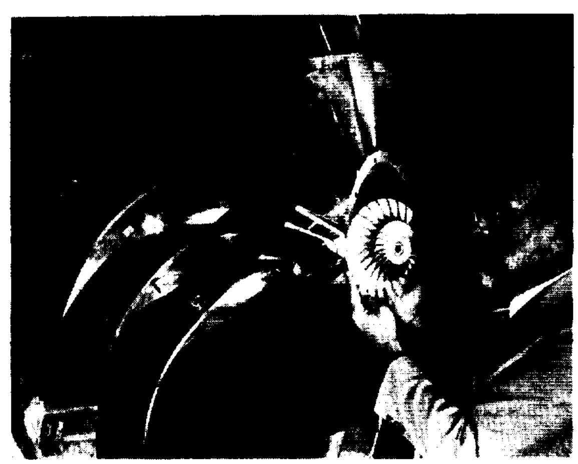

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Figure 19. - Large, low-speed centrifugal compressor.

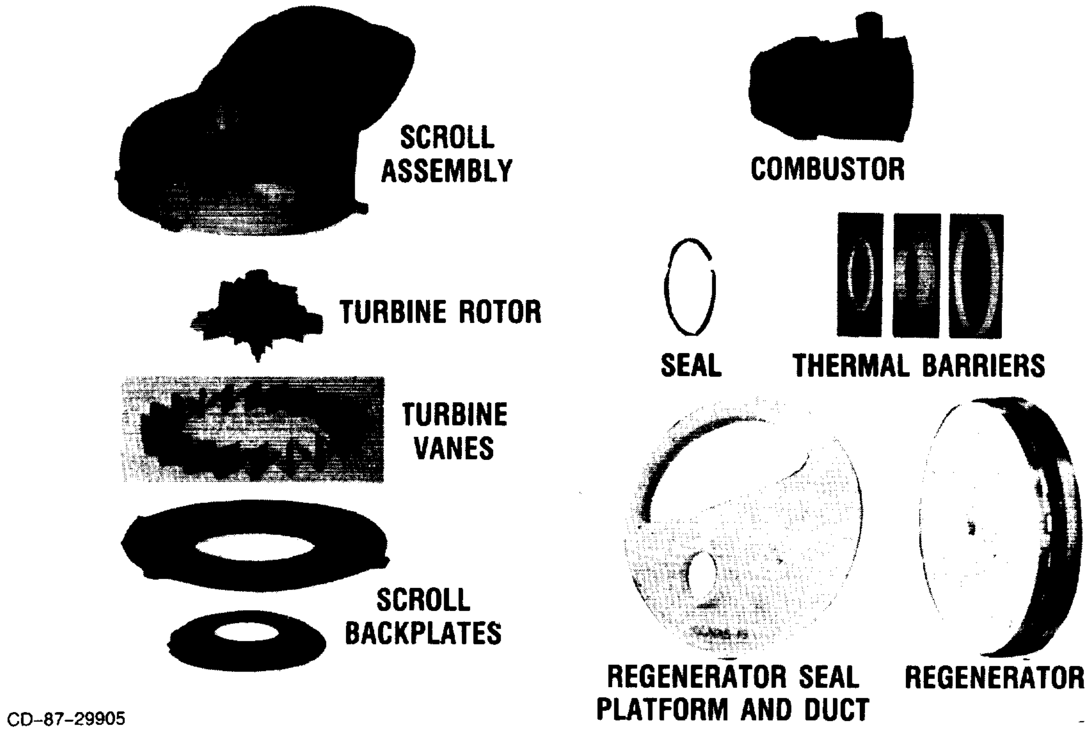

Figure 20. - Advanced ceramic engine components, Lewis/DOE Automotive Gas Turbine Program.

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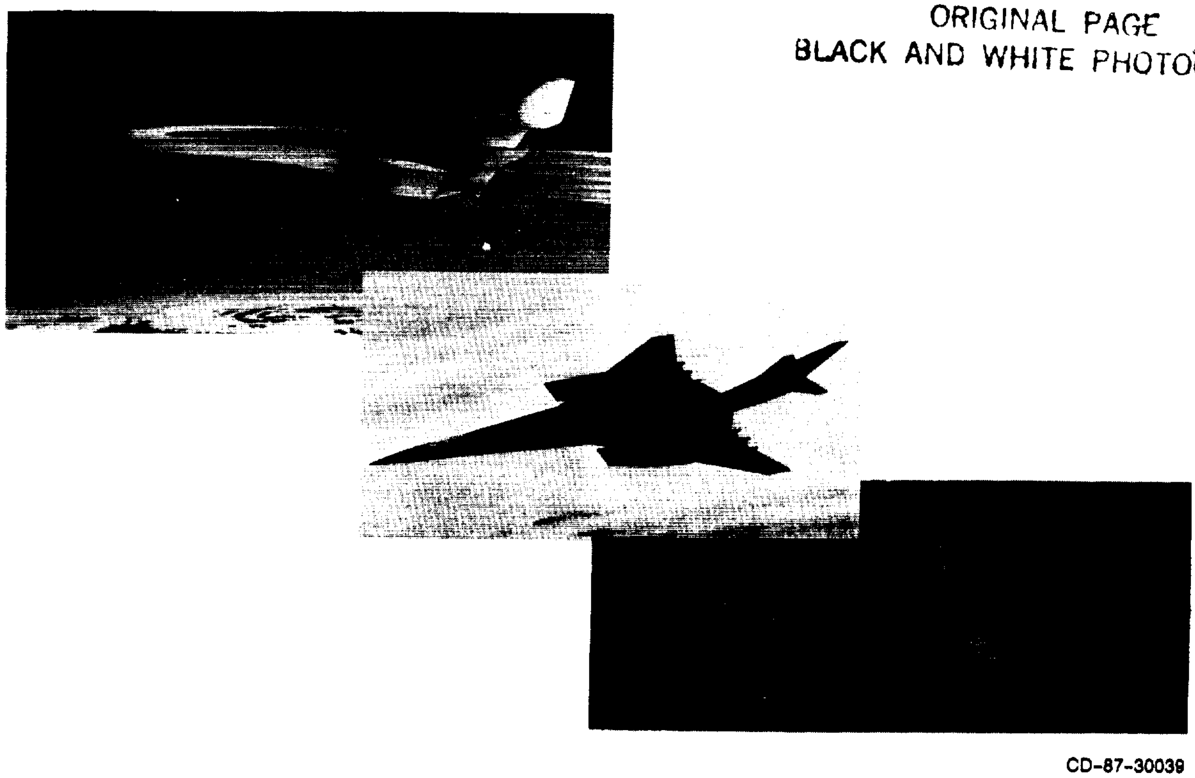

Figure 21. - Aircraft requiring advanced propulsion for long-range supersonic flight.

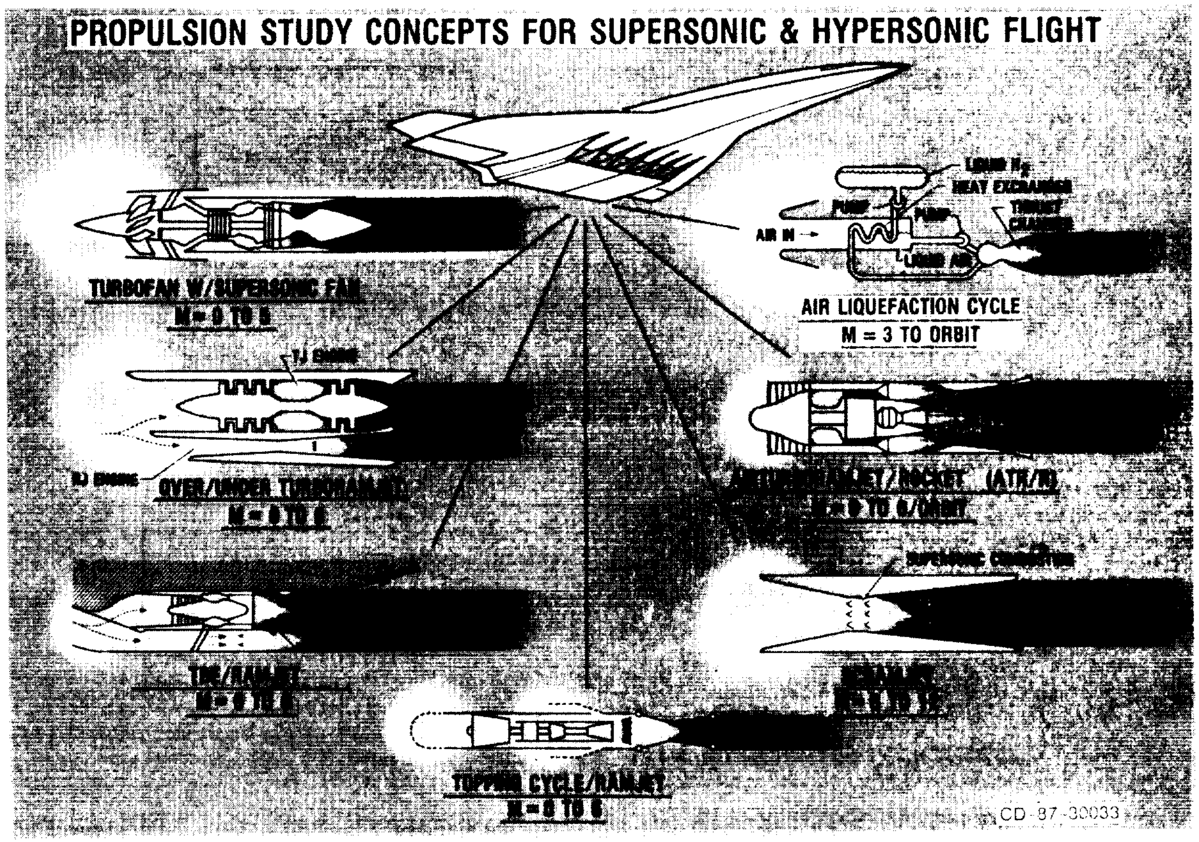

Figure 22. - Advanced propulsion study concepts for supersonic and hypersonic flight.

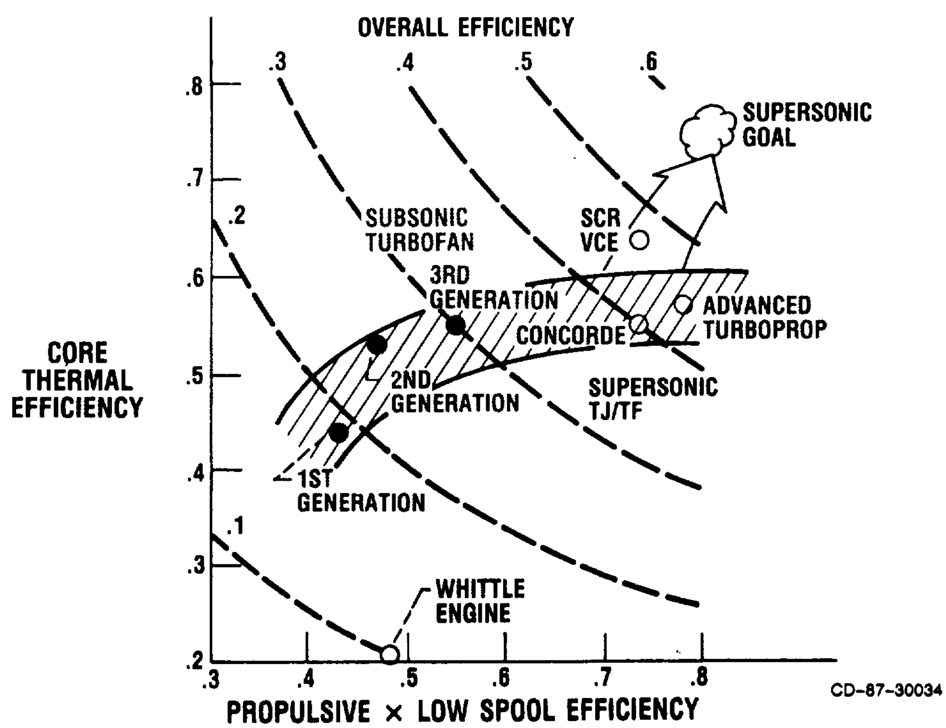

Figure 23. - Turbine engine efficiency goal for high-speed supersonic cruise.

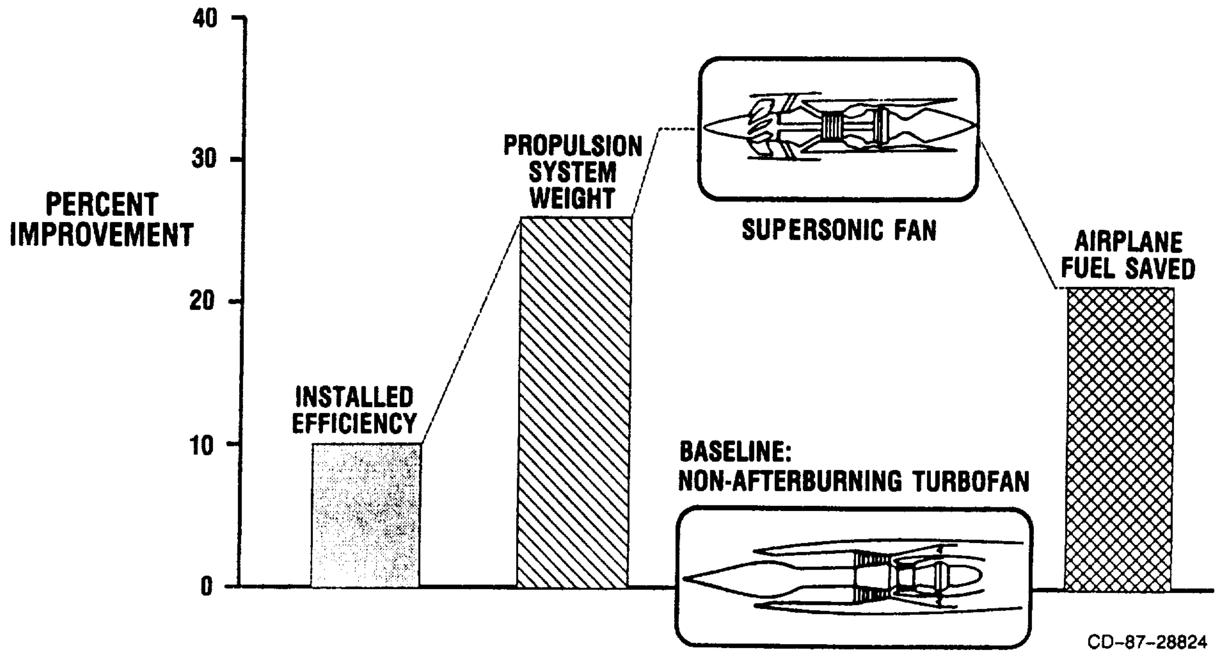

Figure 24. - Supersonic throughflow turbofan benefit for a 300-passenger, Mach 3 commercial transport with 5500-nmi range.

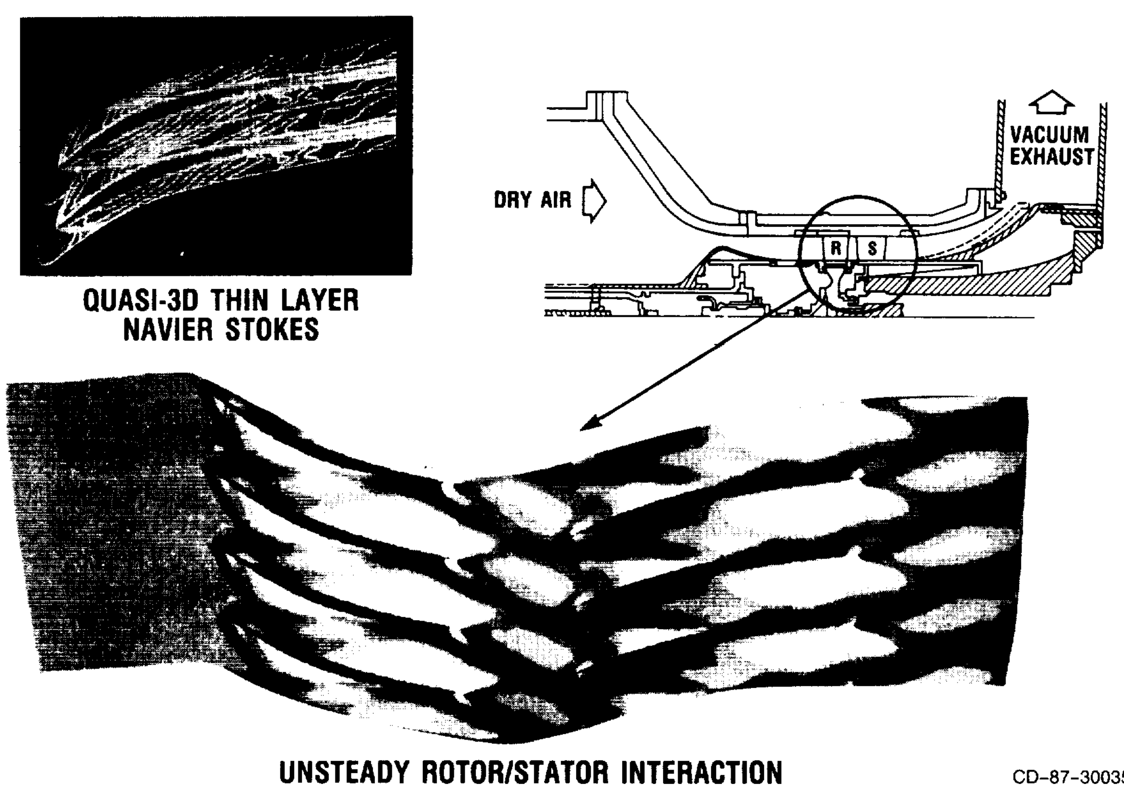

Figure 25. - Hardware and analysis for supersonic fan feasibility demonstration.

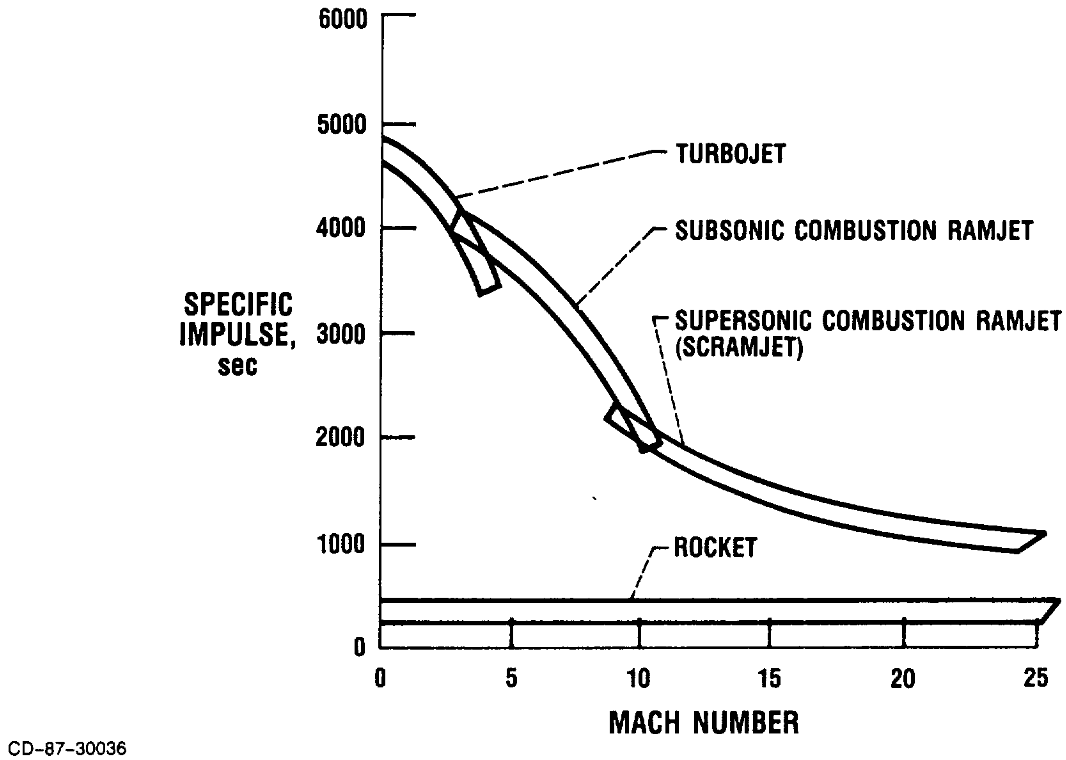

Figure 26. - Performance comparison of high-speed airbreathing and rocket propulsion.

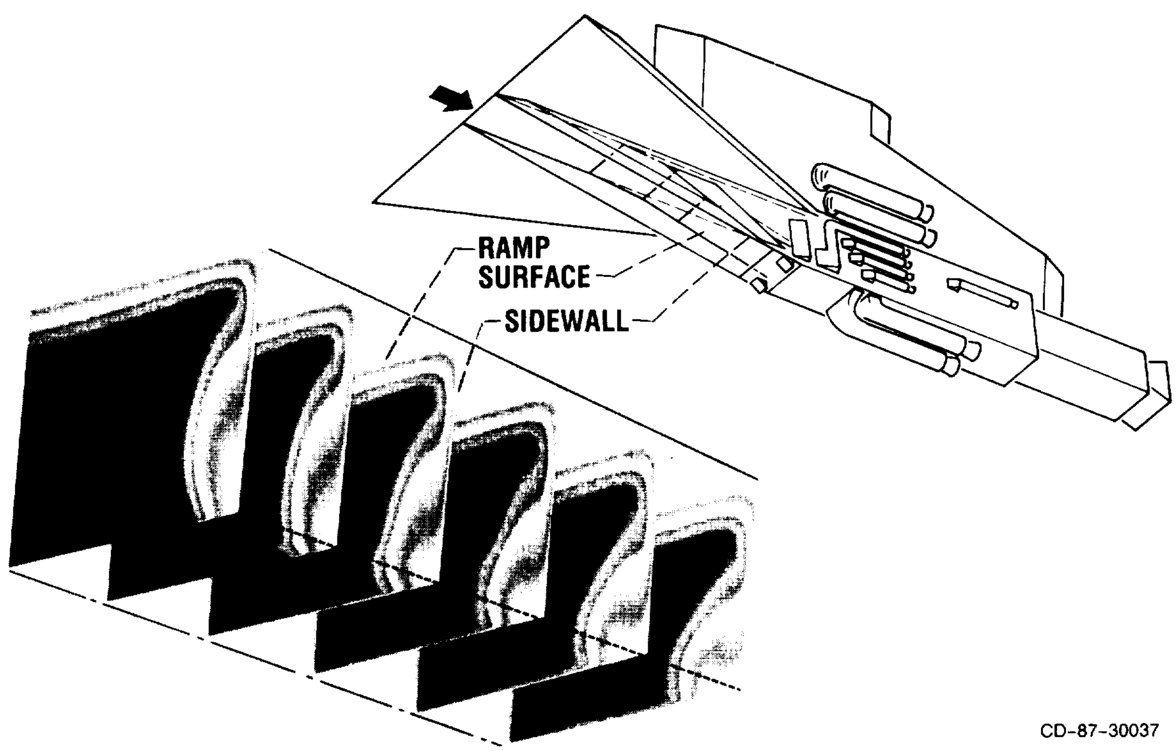

Figure 27. - Test model and analysis for investigation of Mach 5 inlet concept.

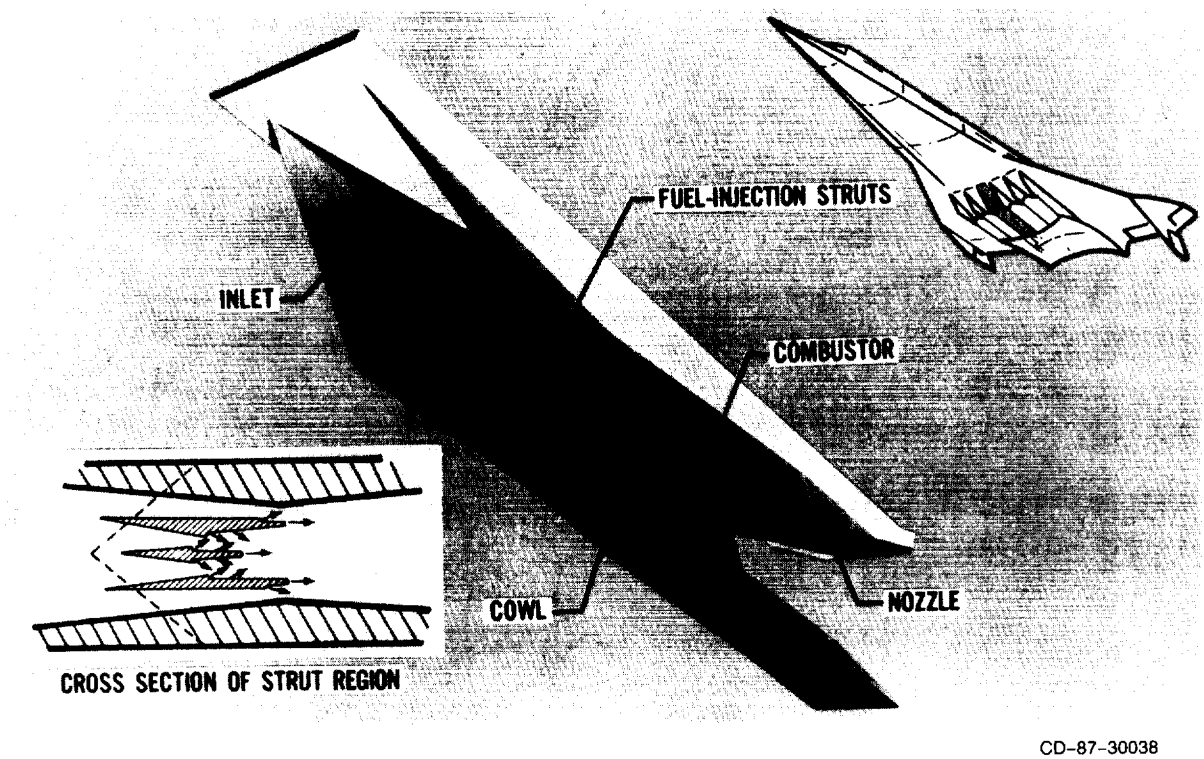

Figure 28. - Langley Research Center concept for airframe integrated supersonic combustion ramjet (scramjet).